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Sequential Geoacoustic Filtering and Utilizing Ambient Noise for Geoacoustic Inversion

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LONG-TERM GOALS

The development of new geoacoustic inversion methods, their use in the analysis of shallow water experimental data, and evaluation of geoacoustic model and parameter uncertainties including the mapping of these uncertainties through to system performance uncertainties.

OBJECTIVES

Analysis of geoacoustic inversion data collected from various experiments. Of specific technical interest are: (1) development of methods to track the environmental parameters using sequential filtering, (2) use of ambient noise for estimation of seafloor structure parameters, and (3) the development of new inversion methods for use into the kHz frequency regime.

APPROACH

1. Sequential filtering

A common feature of inverse problems in ocean acoustics is that estimates of underlying physical parameters are extracted from measured acoustic data. Geoacoustic inversion has been approached in the same framework, estimating, in addition to source location, ocean environment parameters and their uncertainty. Often, those parameters evolve in time or space, with acoustic data arriving at consecutive steps. Information on parameter values and uncertainty at preceding steps can be invaluable for the determination of future estimates but is often ignored.

Sequential Bayesian filtering, tying together information on parameter evolution, a physical model relating acoustic field measurements to the unknown quantities, and a statistical model describing random perturbations in the field observations, offers a framework for the solution of such problems.

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2. Extracting information from noise cross-correlations

We have focused extensively on extracting information from noise in ocean acoustics with both theoretical work as well as experimental work. The passive fathometer is based on relating the down- and up-going signals on the array and can be implemented in the time or frequency domain. Here, we are exploring the passive fathometer by aligning arrivals using phase information from the fathometer (currently only the magnitude is used). We have evidence that the vertical fathometer array moves with the waves on the sea surface. Thus if we can correct for this movement it will be possible to align the reflections better and then average the reflection time series with phase as opposed to just using the envelope. This should give sharper definition of the seafloor and sub bottom reflections and enables estimating environmental geoacoustic parameters in addition to depths of reflecting layers. We also are exploring accelerating convergence for the noise cross-correlation by various signal processing strategies, e.g. averaging, rejecting interference dominated time series, eigenvalue/eigenvector decomposition, and focusing on specific arrivals using beamforming.

WORK COMPLETED

One application of passive estimation of the time-domain Green's function is in the use of cross-correlations of upward and downward pointing vertical line array beams observing ambient noise to extract seabed layer structure (i.e. a passive fathometer) [Traer et al., 2011, 2012]. This so called passive fathometer technique exploits the naturally occurring acoustic sounds generated on the sea-surface, primarily from breaking waves. The method is based on the cross-correlation of noise from the ocean surface with its echo from the seabed, which recovers travel times to significant seabed reflectors. To limit averaging time and make this practical, beamforming is used with a vertical array of hydrophones to reduce interference from horizontally propagating noise. The initial development used conventional beamforming, but significant improvements have been realized using adaptive techniques. An analytical model is presented in [Traer et al., 2011] for the passive fathometer response to ocean surface noise, interfering discrete noise sources, and locally uncorrelated noise in an ideal waveguide. The leading order term from the ocean surface noise produces the cross-correlation of vertical multipaths, yielding the depth of sub-bottom reflectors.

We have explored incorporating Kalman and particle filter tracking techniques into the geoacoustic inversion problem [Yardim 2011a, 2011b, 2011c, Michalopoulou 2012]. This enables spatial and temporal tracking of environmental parameters and their underlying probability densities, making geoacoustic tracking a natural extension to geoacoustic inversion techniques.

RESULTS

In many cases, it is of interest to estimate geoacoustic parameters over a larger spatial region rather than just the parameters characterizing propagation between a fixed source and receiver (or receiving array) location. Data might be available at a moored vertical receiving array from a towed acoustic sound source or a source might be received by a towed horizontal array. In both cases, the typical approach would be to treat each record of data independently of the others and carry out a full geoacoustic inversion for every record resulting in a sequence of geoacoustic parameter estimates and, in some cases, posteriori probability densities of the environmental parameters. The latter enables the environmental uncertainty to be projected into other waveguide characterizations such as propagation loss and its uncertainty.

In a review paper we have studied the basis and use of sequential filtering in ocean acoustics [Yardim 2011]. Sequential filtering provides a consistent framework for estimating and updating the unknown parameters of a system as data become available, see Figs. 1-2. Despite significant progress in the general theory and implementation, sequential Bayesian filters have been sparsely applied to ocean acoustics. The foundations of sequential Bayesian filtering with emphasis on practical issues are first presented covering both Kalman and particle filter approaches. Filtering becomes a powerful estimation tool, employing prediction from previous estimates and updates stemming from physical and statistical models that relate acoustic measurements to the unknown parameters. Ocean acoustic applications are then reviewed focusing on the estimation of environmental parameters evolving in time or space. Some possible scenarios for geoacoustic inversion are shown in Fig. 3.

A new direction is taken in Menon [2012] where random matrix theory is used to analyze noise cross spectral density matrices. Isotropic noise fields are often used to model environmental noise surrounding an array of sensors. For a line array of equidistant sensors in such a noise field, the true covariance matrix of the observations in the frequency domain is a symmetric Toeplitz sinc matrix. In this article, we derive the eigenvalues of the true covariance matrix as the size of the matrix approaches infinity. For arrays spaced at less than half a wavelength apart, the covariance matrix is shown to be rank deficient and this has implications in techniques such as adaptive beamforming, which require the inverse covariance matrix. The zero eigenvalues are related to classical array processing concepts such as the invisible region in frequency-wavenumber space (region where there is no propagating energy, but a spectrum can be calculated). Using random matrix theory, we derive the egenvalue density of the sample noise covariance matrix, whose knowledge is useful in reliable signal detection. An example of such processing is seen in Figure 4.

Some of our results have been demonstrated in two JASA letters. In the first letter [Gerstoft and Hodgkiss, 2011], we demonstrate how beampatterns of two-dimensional random arrays can be improved using convex optimization. In the second letter [Yardim et al, 2011b], the effects of frequency selection on source localization and geoacoustic inversion methods that use frequency coherent objective functions. Matched-field processors based on frequency-coherent objective functions often have rapidly fluctuating range ambiguity surfaces. Insufficient sampling in the frequency domain results in range aliasing terms that affect geoacoustic inversion. Range aliasing and its effects on source localization and environmental parameter inversion are demonstrated on data collected during the MAPEX2000 experiment. Guidance for frequency selection to avoid range aliasing is provided.

IMPACT / APPLICATIONS

Geoacoustic inversion techniques are of general interest for the estimation of waveguide parameters thus facilitating system performance prediction in shallow water. Natural transition paths for these results will be the PEO-C4I Battlespace Awareness and Information Operations Program Office (PMW-120) and the Naval Oceanographic Office.

RELATED PROJECTS

None.

PUBLICATIONS

Gerstoft, Peter and WS Hodgkiss (2011), Improving beampatterns of 2D random arrays using convex optimization, J Acoust. Soc. Am EL, 129, EL135-140 DOI:10.1121/1.3556896, April 2011. [published, refereed]

Menon, Ravishankar, Peter Gerstoft, and William S. Hodgkiss (2012), Asymptotic Eigenvalue Density of Noise Covariance Matrices, IEEE Signal processing. [submitted]

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Traer, James, Peter Gerstoft, and W. S. Hodgkiss (2011), Ocean bottom profiling with ambient noise: a model for the passive fathometer, J. Acoust. Soc. Am., 129, 1825-1836, doi:10.1121/1.3552871, April 2011. [published, refereed]

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Yardim, Caglar, Zoi-Heleni Michalopoulou, and Peter Gerstoft (2011a), An overview of sequential Bayesian filtering in ocean acoustics, IEEE Oceanic Eng 36(1), 73-91, Doi:10.1109/JOE.2010.2098810. [published, refereed]

Yardim, Caglar, Peter Gerstoft and WS Hodgkiss (2011b), Range Aliasing in Frequency Coherent Geoacoustic Inversion, J Acoust. Soc. Am EL, 130, EL154-EL160, Doi:10.1121/1.3630021. [published, refereed]

Yardim, Caglar, Peter Gerstoft and WS Hodgkiss (2011c), Sequential geoacoustic inversion at the continental shelfbreak, J Acoust. Soc. Am, 130, [in press, refereed]

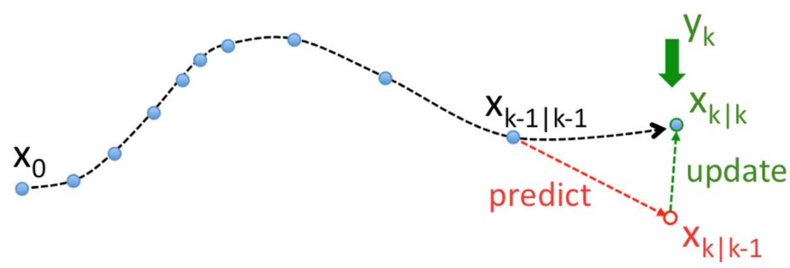

Figure 1. Sequential Bayesian filtering. From state x_{k-1}, state x_k is first predicted via the state equation, providing $x_{k|k-1}$. As data y_k becomes available, the observation equation is employed to update state $x_{k|k-1}$, providing $x_{k|k}$.

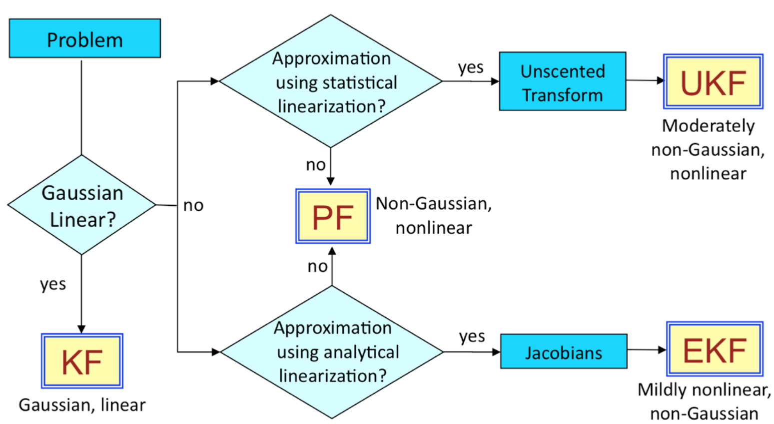

Figure 2. A quick guide to filter selection leading to the Kalman filter (KF), extended Kalman filter (EKF), unscented Kalman filter (UKF), and particle filter (PF).

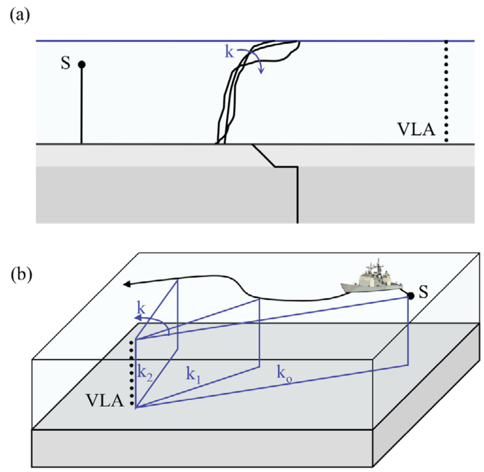

Figure 3. Geoacoustic environmental tracking: (a) Temporal tracking of the ocean sound speed profile for a fixed-receiver and a fixed-source and (b) tracking of the changing environment between the receiver and a moving source. Here shown for a vertical line array (VLA) of receivers.

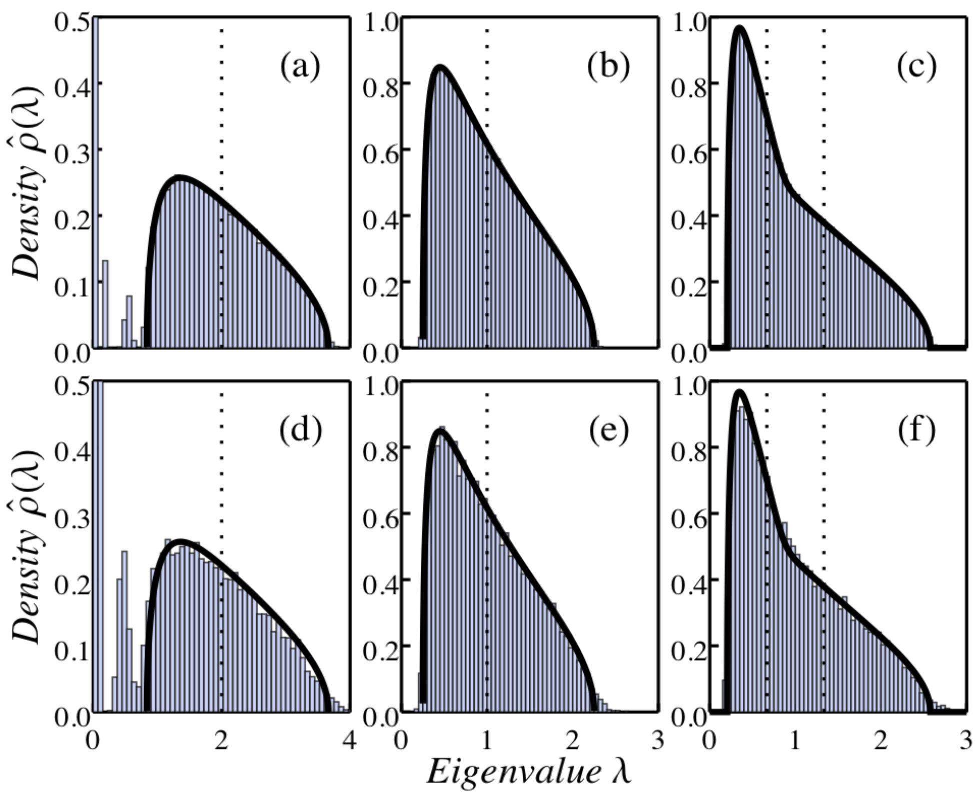

Figure 4. Asymptotic eigenvalue density (solid line) and the empirical eigenvalue density, with N = 100 array elements, ν = 1/4 (ratio of number of sensors to number of snapshots) and spacing to wavelength ratios β of (a) 1/4 (b) 1/2 and (c) 3/4. (d,e,f): Same as in (a,b,c) except with N = 20. The dotted lines show the locations of the distinct non-zero true eigenvalues. For more information see Menon [2012].